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Radiation from the NuMI RAW Room

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Introduction

The NuMI RAW room (Figs. 1,2) is where the water-cooling systems for the horns, target and the decay pipe [1-3] are located. The cooling water used for these devices becomes activated, hence the name Radio-Active Water (RAW). The dose rate at the gate is due to the radiation leaking through the concrete wall, through the gaps between the top of the walls and the rock ceiling and through the RAW room doorway. This note describes the calculations used to assess the levels of radiation inside and outside of the RAW room, and its radiological implications.

Input Parameters

The calculations of the radioactivity levels of the cooling tanks are described elsewhere.[4] It is assumed that the beam line has been operating for one year, the entire induced radioactivity is collected in the tanks and the cooling time is zero. These assumptions will be discussed further at the end of this note. Table 1 gives the total activity for each cooling tank. Tritium is not a gamma emitter and ^{7}Be-decay by photon emission which has a 10.3% branching ratio. Since the dose rate outside a tank is due to gamma rays only, no tritium activity and 10.3% of the ^{7}Be have been included in the dose calculations.

RAW Source	**Horn1**	**Horn2**	**Target**	**Decay Pipe**
Activity (Bq/cc)	6.63E+06	1.96E+06	2.47E+06	3.28E+03
Dose Rate (mrad/hr)	66627	19683	9763	32
Tank Volume (Gal.)	100	100	30	100

Table 1. Gamma ray activity levels, dose rates and volumes of the RAW tanks after one year of beam operation and no cooling time.

For source dose rate calculations it is assumed that the radiation is due to 511 keVgamma rays, which is true for ^{15}O, ^{13}N and ^{11}C, but slightly overestimates the dose due to ^{7}Be 477 keV photons.[5]

It is assumed that the concrete wall between the RAW room and the hallway is 3 ft. thick, the ceiling height is 13 ft. everywhere, the RAW room doorway is 3.5 ft. wide and the gate is about 23 ft. and 8 inches from the north wall. It was further assumed that the shield walls are 10 ft. high.

Methodology

The radiation from the RAW tanks reaches the gate in the hallway through **four** paths: through the southeast gap between the rock and the wall of RAW room, through the 3 ft.

concrete east wall of the RAW room, through the doorway and through the gaps between the rock ceiling and the tops of the shielding walls. The third and the fourth path are treated as photons propagating through a labyrinth.

The cooling tanks are modeled as self-absorbing cylindrical volume sources. The dose rate from such a source at a point behind a shield wall is given by,[6-10]

$$\dot{D} = \frac{BS_V R}{p} G(k, p, m_s R, b_1),$$

$$k = \frac{H}{2R} \quad , \qquad p = \frac{a}{R},$$

where b_1 is the shield thickness expressed in mean free path lengths,
S_V is the specific activity of the volume source,
a is the distance from the center of the cylinder to measurement point,
R is the radius of the cylinder,
H is the height of the cylinder,
m_s is the attenuation coefficient of the medium (water) for 0.511 MeV gamma rays[5],
B is the buildup factor for 0.511 MeV photons in the shield material,
$G(k,p,\mu_s R,b_1)$ is an integral function, which is evaluated numerically and tabulated for different values of k, p and b_1[7-9]

This equation was used in two ways. For the calculation of radiation leaking through the concrete wall, b_1 was set equal to the thickness of the wall. For the source terms calculations for the labyrinths, b_1 was set to zero.

Then radiation dose at point P (Fig. 1) is the sum of the radiation from each tank. Horn1 tank is the closest to the south wall of the RAW room, the radiation from the other tanks would be going through a longer distance through the concrete to get to point P. Table 2 shows dose rates outside the west wall.

RAW Source	**Horn1**	**Horn2**	**Target**	**Decay Pipe**	**Total**
Concrete thickness (in)	36	39.7	47.2	48.4	---
Dose rate at P (mrad/hr)	0.4	0.1	0.0	0.0	0.5

Table 2. Dose rate from each of the concrete tanks behind the 3-ft. west concrete wall at point **P**. The last column is the total dose rate.

The radiation from location P attenuates further as it propagates to the gate by scattering off the walls and by direct propagation. The scattered and direct doses were calculated separately. First, it was assumed that the concrete wall is a 0.5 mrad/hr uniformly distributed source that shines on the opposing wall and the scattered photons reach the gate. This is a simple two-legged labyrinth. For the direct component it was assumed that the section of the concrete wall that blocks the RAW room is a uniform rectangular surface source which makes a ~38° angle with the center of the gate.

The radiation reaching the point Q (Fig. 1) goes through very little concrete (CMU wall) and rock. The results of the calculation of the dose rate at the northeast corner of the hallway outside the door are given in Table 3. Without additional shielding this area will not be allowed to be accessible. An additional 18 inches of equivalent concrete south wall (Fig. 1) is proposed to solve this problem. As the last row of Table 3 shows, the resulting dose rate is acceptable.

RAW Source	Horn1	Horn2	Target	Decay Pipe	Total
Concrete thickness (in)	39.8	23.8	21.7	18.9	---
Dose rate at Q without concrete (.rad/hr)	669.1	135.9	40	0.4	845.4
Dose rate at Q (mrad/hr)	0.00	0.03	0.02	0.00	0.05

Table 3. Dose rate from each of the concrete tanks behind the 18 in. concrete shield at point **Q**. The last column is the total dose rate.

For the radiation t hat comes through the RAW room doorway, b_1 was set to zero (no shield) and the dose rate from each tank (volume source) was calculated. Then the propagation of the gamma rays from each of the sources through a three-legged labyrinth (see red line in figure 1 as an example) was calculated using photon albedo coefficients[6,9,11] using,

$$H_j = \frac{H_o d_o^2 \prod_{k=1}^{3} a_k A_k}{\prod_{k=1}^{3} d_k^2},$$

where a_k is the reflection coefficient of the wall,
A_k refer to the area of the photon beam projected on the wall,
d_k is the length of the leg k,
H_o is the dose rate from the tank at a distance d_o,
d_o is the distance at which the source dose rate H_o is evaluated (1 ft.),
k is the leg number.

Details of the application of the above equation are given in reference 11. Table 4 gives the source term and the distance to the north wall and the resulting dose rates at the gate for each source.

RAW Source	Horn1	Horn2	Target	Decay Pipe	Total
H_o (mrad/hr)	66632	19682	9762	33	(mrad/hr)
" d_k" Distance to North Wall (ft)	17.3	10	4.2	9.7	
Dose at the gate (mrem/hr)	2.0E-02	5.9E-03	2.9E-03	9.8E-06	0.029

Table 4. Labyrinth sources and the dose rates at the gate due to each source.

To calculate the radiation leaking through the gaps between the tops of the walls and the rock ceiling it was assumed all sources are at 6.5 ft. from the ground. The resulting radiation was then propagated through a 3-legged labyrinth composed of a vertical 6.5 ft. long cross section of the RAW room, a straight path from the center of the RAW tank to above the gate (second leg, parallel to the floor) with a conservative cross section 21 ft. by 3.5 ft. and a vertical turn down to the height of 6.5 ft. with a cross sectional area equal to the ceiling area between the two utilities rooms (Figs. 1 and 2). The resulting dose rate from each tank is given in Table 5.

RAW Source	**Horn1**	**Horn2**	**Target**	**Decay Pipe**	**Total** (mrad/hr)
Length of the second leg (ft)	21.6	24.5	28.9	17.9	
Dose at the gate (mrem/hr)	7.16E-01	1.64E-01	5.86E-02	5.16E-04	0.94

Table 5. Dose rates at the gate due to each source from the radiation coming from the gaps between the top of the walls and the rock roof.

After 4 hours of cooling almost all of the short -lived isotopes have decayed and more than 95% of the remaining activity will be due to ^{7}Be in the DI-bottles. To estimate the required shielding for the DI-bottles, it was assumed that all of the ^{7}Be from each system is trapped in its DI-bottle. As Table 6 shows, the dose rate from some of the DI-bottles are significant. The calculations show that about 1.5 inches of lead-equivalent shielding is required to make the area around the horn1 and horn2 bottles acceptable for maintenance work on the RAW systems.

Pb Shield Thickness (in)	Pb Atten. Fact. For 511 keV	**Horn1** DI-bottle (mrem/hr@1ft)	**Horn2** DI-bottle (mrem/hr@1ft)	**target** DI-bottle (mrem/hr@1ft)	**DP** DI-bottle (mrem/hr@1ft)
0	1	1134	335	166	1
1	1.58E-02	17.9	5.3	2.6	0.0
1.5	1.74E-03	**2.0**	**0.6**	**0.3**	**0.0**

Table 6. Dose rates from ^{7}Be only in the DI-bottles for different lead-equivalent shielding thicknesses.

Results and Discussions

The 18-inch concrete equivalent south shield wall should be 9 ft. wide to block the radiation from the Horn1 tank adequately. Horn1 and horn2 DI-bottles have the highest dose rates and require 1.5" of lead equivalent shielding to reduce the doses to less than 3 mrem/hr. Table 7 gives the total dose rate from all the sources that were discussed above. The total dose rate from all pathways to a person standing outside the RAW room door is about 1.0 mrem/hr. About 90% of this dose is from the opening between the top of the walls and the rock ceiling.

The total dose rate of 1.0 mrem/hr is a conservative estimate based on one-year full intensity operation without any time to cool down. No credit is taken for the shielding due to all the pipes, I-beams and other equipment. Most of ^{7}Be will be trapped in the DI-bottles and filters, which are locally shielded.[4] Seventy percent of the activity is due to the isotope ^{15}O, which has a 2-minute half-life. A 2-minute transit time from the target hall to the tank can reduce the above rates by 30%. The radiation leakage from target hall through the RAW room penetration [12] (0.03 mrem/hr) is not included in these calculations, since most of it is due to the prompt radiation and is insignificant compared to the radiation from the RAW tanks.

RAW Source	Horn1	Horn2	Target	Decay Pipe	A. Total
	(mrad/hr)	(mrad/hr)	(mrad/hr)	(mrad/hr)	(mrad/hr)
Labyrinth dose rate	2.0E-02	5.9E-03	2.9E-03	9.8E-06	.03
Concrete wall leakage from P (Direct)	3.0E-02	1.0E-02	3.7E-03	3.6E-06	0.04
Concrete wall leakage from P (Scattered)	1.4E-04	3.6E-05	0.0E+00	0.0E+00	0.0
South shield wall leakage at Q (Direct)	0.00	0.03	0.02	5.8E-04	.05
Ceiling shine dose rate	7.16E-01	1.64E-01	5.86E-02	5.16E-04	0.94
				Total Dose rate (mrem/hr) =	**1.06**

Table 7. All the components of radiation that contribute to the net dose rate at the gate.

Under the above assumptions RAW room is inaccessible. Four hours of cool down is required before access. However, remote monitoring of the actual dose rates is possible, and the responsible Radiological Control Organization will use this information to control the actual required cooling time.

Based on the above assumptions and results the dose rate at the gate in the hallway is conservatively about one mrad/hr. The area outside the door should be posted as CONTROLLED AREA with Minimal Occupancy classification. A second gate is placed at 14.5 ft. from the RAW room gate to separate the minimal occupancy area from the unlimited occupancy area. The Power Supply room next door will not require any radiological posting due to the radiation leakage from the RAW room.

References

1. NuMI Design Parameter Book
   http://www-numi.fnal.gov:8875/numwork/design_params.txt

2. Outfitting Drawings 6-7-6

- A1: Pre Target & US Target Hall Plan, Elevation
- A2: Target Hall Plan
- A34: Target Hall Elevation, Transmission Line, RAW Penetration diameters
- M7: Target Hall Plan - labyrinth, support rooms, penetrations

3. NuMI technical design Handbook, chapter 4, also at http://www-numi.fnal.gov:8875/numwork/tdh/tdh_index.html

4. K. Vaziri, "Calculation of the Induced Radioactivity Levels and Hydrogen Gas Evolution in the NuMI RAW Systems", RP-NOTE-140 (June 2003)

5. NIST database http://physics.nist.gov/PhysRefData/XrayMassCoef/cover.html

6. A. B. Chilton, J. K. Shultis, and R. E. Faw, Principles of Radiation Shielding, Prentice-Hall, Inc., New Jersey (1984).

7. Anthony Foderaro, The Photon Shielding Manual, Pennsylvania State University (1978).

8. R. G. Jaeger, E. P. Blizard, A. B. Chilton, M. Grotenhuis, A. Honig, T. A. Jaeger, and H. H. Eisenlohr, Eds., Engineering Compendium on Radiation Shielding, Springer-Verlag, New York (1968).

9. E. A. Burrill, Chair, J. R. Beyster, G. L. Brownell, A. B. Chilton, J. Haimson, C. J. Karzmark, W. E. Kreger, J. M. Wyckoff, *Radiation protection design guidelines for 0.1 -100 MeV particle accelerator facilities*, NCRP Report 51 (National Council on Radiation Protection and Measurements, Bethesda, MD, 1977)

10. K. R. Kase and W. R. Nelson, Concepts of Radiation Dosimetry, Pergamon Press, New York (1978).

11. J. D. Cossairt, "Radiation physics for personnel and environmental protection", Fermilab Report TM 1834, February 2003.

12. K. Vaziri, "Radiation from the NuMI Labyrinths and Penetrations", in preparation.

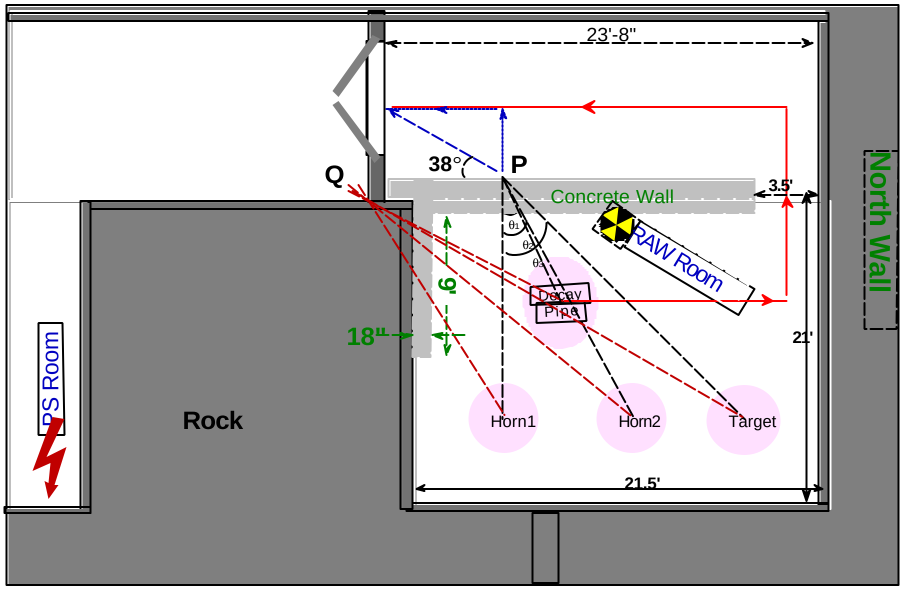

Figure.1. Plan view of the RAW room. Point P is the location of the highest dose rate leakage. The red line shows an example of path from one of the sources through the labyrinth.

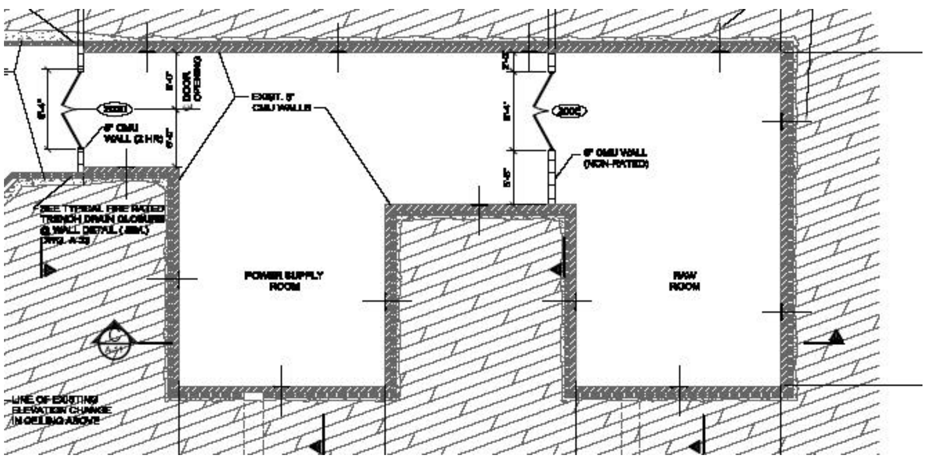

Figure 2. Plan view showing the NuMI Power Supply room and the RAW room. Dashed lines show the locations of the penetrations into the two rooms.

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